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Simulation and optimization of stand-alone hybrid renewable energy systems

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A B S T R A C T

Stand-alone hybrid renewable energy systems usually incur lower costs and demonstrate higher reliability than photovoltaic (PV) or wind systems. The most usual systems are PV–Wind–Battery and PV–Diesel–Battery. Energy storage is usually in batteries (normally of the lead-acid type). Another possible storage alternative, such as hydrogen, is not currently economically viable, given the high cost of the electrolyzers and fuel cells and the low efficiency in the electricity–hydrogen–electricity conversion. When the design of these systems is carried out, it is usually done resolve an optimization problem in which the Net Present Cost (NPC) is minimized or, in some cases, in relation to the Levelized Cost of Energy (LCE). The correct resolution of this optimization problem is a complex task because of the high number of variables and the non-linearity in the performance of some of the system components. This paper revises the simulation and optimization techniques, as well as the tools existing that are needed to simulate and design stand-alone hybrid systems for the generation of electricity.

Contents

1. Introduction

Various aspects must be taken into account when working with stand-alone hybrid systems for the generation of electricity. Reliability and cost are two of these aspects; it is possible to confirm that hybrid stand-alone electricity generation systems are usually more reliable and less costly than systems that rely on a single source of energy [1,2]. In various research papers [3–5], it has been proven that hybrid renewable electrical systems in off-grid applications are economically viable, especially in remote locations. In addition, climate can make one type of hybrid system more profitable than another type. For example, photovoltaic hybrid systems (Photovoltaic–Diesel–Battery) are ideal in areas with warm climates [6].

On the other hand, various mathematical models of the elements that make up these systems have been used, as well as various design and simulation models. The complexity of the models of the components of the hybrid systems mainly depends on the type of application (simulation, design, etc.). The models usually used for the components of the most common hybrid systems (photovoltaic, wind, diesel and batteries) are shown in [7].

This paper will review the simulation and design models of the hybrid systems that have been used up to this moment in time, indicating which tools have been developed for this purpose. Thus, in the first place, we have the review carried out on the design and control of the hybrid systems, such as photovoltaic (PV) and/or wind and/or diesel with battery storage. Then the review of the

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design and control of stand-alone hybrid systems, including energy storage in hydrogen, is shown. Then the existing papers that have simultaneously considered various objectives in the design of these systems (Multi-Objective design) are detailed. To conclude, the most relevant characteristics of the simulation and design software tools used in hybrid systems are indicated, as well as the conclusions reached from the full review that has been completed.

2. Design and control of PV and/or wind and/or diesel hybrid systems with energy storage in batteries

PV–Diesel, PV–Wind, PV–Wind-Diesel, and Wind–Diesel hybrid systems with energy storage in batteries have been studied by various authors. These systems have been installed for a number of decades, although their systems would be substantially improved if optimization methods were applied. Below, some of the most relevant papers that have been written are chronologically detailed. In the first place, those that have focused on design (without optimization) and simulation are shown, and then those papers that have studied the possible strategies for the control of hybrid systems.

2.1. Design and simulation

Gavanidou et al. [8] propose a probabilistic model in reference to the simulation of Wind–Diesel systems (no batteries) based on the use of statistical data of loads and wind speeds. In reference to this, the annual production of electricity of wind turbines is calculated, as well as the annual cost to operate the diesel engine, the probability of load loss and the energy not supplied, proposing a maximum penetration (% of energy supplied by the wind turbines) for the system in terms of supplying the forecasted demand.

McGowan and Manwell [9] describe the latest advances in PV–Wind–Diesel–Batteries hybrid systems, using data from hybrid systems in various locations in the world. Additionally, the simulation tools applied to these systems are described (mainly focusing on HYBRID2 [10]). In a later paper [11] the designs for PV–Wind–Diesel–Battery systems for various applications in South America are described.

Karaki et al. [12] present a series of simulation algorithms of PV–Wind–Battery systems, economically valuing the hybrid systems and obtaining a limit in terms of battery capacity, depending on the desired charging/discharging cycle time.

Various interesting papers have studied the performance of PV–Wind–Diesel–Battery systems. Elhadidy [3,13] studied the performance of possible variances of those systems; Schmidt and Patterson [14] studied the effect of energy demand management on PV–Wind–Diesel–Battery systems.

Wies et al. [15] present a simulation work, using Simulink, of a real hybrid PV–Diesel–Battery system located in Alaska, comparing it with a system with only a diesel generator and another Diesel–Battery system to supply energy for the same load. Contaminating emissions were evaluated (CO_2, NO_x and particles) for the various cases, comparing the results with those obtained by means of HOMER [16] software. Additionally, the global efficiency of the system and its costs were determined. The results obtained indicate that the system with only a diesel generator had a lower installation cost, but higher operation and maintenance costs; additionally, it was less efficient and released more contaminating emissions than the PV–Diesel–Battery system.

Finally, Nfah et al. [17] show the design of a PV–Wind–Diesel–Battery system for remote areas of the far northern province of Cameroon.

2.2. Optimization

Numerous papers have been written about the optimum economic designs of PV and/or Wind and/or Diesel systems with energy storage in batteries. Table 1 shows a summary of the most relevant papers published to date.

Usually, the optimum design is carried out minimizing the Net Present Cost (NPC: investment costs plus the discounted present values of all future costs during the lifetime of the system) or by minimizing the Levelized Cost of Energy (LCE: total cost of the entire hybrid system divided by the energy supplied by the hybrid system). Additionally, restrictions are usually included that are applied to reliability, evaluating the same by means of one of the following parameters:

- Loss of Load Probability (LOLP): power failure time period divided by a given period of time (generally one year).
- Loss of Power Supply Probability (LPSP): probability that an insufficient power supply will result when the hybrid system is unable to satisfy the load demand.
- Unmet Load (UL): non-served load divided by the total load of a period of time (normally one year).

Table 1
Publications on optimization of PV and/or Wind and/or Diesel hybrid systems with battery energy storage.

	PV–Diesel–Batteries	PV–Wind–Batteries	PV–Wind–Diesel–Batteries	Wind–Diesel–Batteries	Optimization of components	Optimization of control strategy
Borowy and Salameh, 1996		×			×	
Chedid and Saliba, 1996			×		×	
Kaiser et al., 1997	×				×	×
Morgan et al., 1997	×				×	
Seeling-Hochmuth, 1997			×		×	×
El-Hefnawi, 1998	×				×	
Protogeropoulos et al., 1998		×			×	
Kellogg et al., 1998		×			×	
Elhadidy and Shaahid, 1999				×	×	
Dufo-López and Bernal-Agustín, 2005	×				×	×
Koutroulis et al., 2006		×			×	
Shaahid and Elhadidy, 2006	×				HOMER	
Ashok, 2007			×		×	
Yang et al, 2007, 2008		×			×	
Diaf et al, 2008		×			×	
Dalton et al., 2008			×		HOMER	
Himri et al., 2008				× No batteries	HOMER	
Shaahid and El-Amin, 2008	×				HOMER	

Borowy and Salameh [18] present a method to optimize the size of the PV generator and the capacity of the batteries in PV–Wind–Battery systems. As initial data, the desired UL value is considered. The wind turbine, the type of panel, and the type of battery are fixed. Changing the number of photovoltaic panels and the number of different battery systems that comply with the maximum UL value are achieved. Said systems are economically assessed, and the one with the lowest cost is selected.

Chedid and Saliba [19] propose a method for the optimum design of autonomous hybrid PV–Wind–Diesel–Battery systems by means of the economic optimization of the system, applying lineal programming. Kaiser et al. [20] present a method to simultaneously optimize the control strategies and the characteristics of the elements of PV–Diesel–Battery systems, as well as *on-line* optimization of the control strategy (redefined during the system operation) based on decision-taking theory. Morgan et al. [21] describe the ARES program on simulation and optimization of hybrid PV–Diesel–Battery systems, where the batteries are modeled with great precision. Seeling-Hochmuth [22] carries out the optimization (minimization of the NPC) of a hybrid PV–Wind–Diesel–Battery system by means of the Genetic Algorithm technique. El-Hefnawi [23] presents an optimization method of PV–Diesel–Battery systems. That method is based on the definition of a model of a diesel generator, and from this, it carries out the optimum dimensioning of the PV generator and of the batteries. Protogeropoulos et al. [24] carry out the optimization of PV–Wind–Battery systems, modifying the size of the batteries until a configuration that ensures sufficient autonomy is achieved. Kellogg et al. [25] present an iterative optimization method for PV–Wind–Battery systems.

Elhadidy and Shaahid [26] have studied the effect of the size of the batteries on the operation hours and on the energy provided by the diesel generator in Wind–Diesel–Battery systems. The diesel generator works only when the wind turbines do not provide sufficient energy and, additionally, the batteries are unable to supply the demand. By changing the size of the batteries, economic optimization of the system is carried out.

Dufo-López and Bernal-Agustín [27] carry out the optimization of hybrid PV–Diesel–Battery systems by means of Genetic Algorithms (GA). In a prior paper [28], they determined the correct performance of GA as a technique for the design of hybrid systems. Thus, by means of GA, the optimum or a very similar system to the optimum can be obtained, with reduced calculation time. The results obtained are compared in the optimization of a hybrid system applying GA with the results reached with an enumerative method (assessing all the possible designs).

Koutroulis et al. [29] present a paper for economic optimization by means of Genetic Algorithms on PV–Wind–Battery systems. Shaahid and Elhadidy [30] use the HOMER software for the economic optimization (minimization of the NPC) of a PV–Diesel–Battery system to supply a shopping center located in Dhahran (Saudi Arabia). Ashok [31] presents an optimization method for PV–Wind–Diesel–Battery systems that includes Micro-hydro. The LCE of all of the possible component combinations is assessed. It is applied to an example located in India.

Yang et al. [32,33] present a method for the optimization of hybrid PV–Wind–Battery systems which minimize the LCE. The optimization is carried out by trying component combinations: changing the number of PV modules, the orientation of PV modules, the rated power of the wind turbine, the tower height of the wind turbine, and the capacity of the battery bank.

Diaf et al. [34] present an application of hybrid PV–Wind–Battery systems in Corsica (France) which minimizes the LCE. Dalton et al. [35] carry out the optimization (minimization of NPC) by means of HOMER in a PV–Wind–Diesel–Battery system in Australia. In addition, simulations of the optimum system are carried out, using HOMER and HYBRIDS [36] for this purpose, comparing the simulations obtained with each of the two programs.

Himri et al. [37] optimize a Wind–Diesel system using HOMER, with no batteries, to supply a remote village in Algeria. Shaahid and El-Amin [38] use HOMER for the optimization of a PV–Diesel–Battery system to supply a remote village in Saudi Arabia.

2.3. Control strategies

In hybrid systems with batteries and without diesel generators, the dispatch strategy is very simple: the battery charges if the renewable energy is in excess after meeting the demand, and the battery discharges if the load exceeds the renewable energy. However, the control strategies of a hybrid system can become very complex if the system includes a diesel generator and batteries, as it is necessary to determine how the batteries are charged and what element (batteries or diesel generator) have priority to supply energy when the load exceeds the energy generated from renewable sources.

Ohsawa et al. [39] apply neural networks to the control strategies of power PV–Diesel systems. Knowing the energy demand and the solar irradiation, dynamic programming is used in order to optimize the operation of the diesel generator, minimizing the fuel costs. For this, an adaptive intelligence strategy is used, comparing the results obtained by applying two types of neural networks.

In 1995, Barley et al. [40] proposed various strategies for the operation of hybrid PV–Diesel–Battery systems. One-hour intervals are considered, during which the system parameters remain constant. They also consider ideal batteries, without taking into account losses or the influence of the cycles in the lifespan of the same. The three basic control strategies proposed are the following:

- *Zero-charge strategy* (*Load Following Diesel*): the batteries are never charged using the diesel generator. Therefore, the Setpoint of the State of Charge (*SOC_Setpoint*) is 0%.
- *Full cycle-charge strategy*: the batteries are charged to 100% of their capacity every time the diesel generator is on (*SOC_Setpoint* = 100%).
- *Predictive control strategy*: the charging of the batteries depends on the prediction of the demand and the energy expected to be generated by means of renewable sources, so there will be a certain degree of uncertainty. With this strategy, the energy loss from the renewable energies tends to decrease.

The authors propose having an optimum point for the *SOC_Setpoint* between 0 and 100% in such a way that the total operation cost of the system is minimal. That is to say, the strategy will be between *Zero-charge* and *Full cycle-charge*.

In 1996, Barley and Winn [41] improved the control strategies model of [40], introducing new parameters that have become of great importance in the control strategies of the software tools HYBRID2, HOMER, and HOGA [42]. The Critical Discharge Power (L_d) is the value as from which the net energy (that demanded by the charges minus that supplied by the renewable sources) is more profitable when supplied by means of the diesel generator than when supplied by means of the batteries (having previously been charged by the diesel generator). The authors propose four control strategies:

- *Frugal Dispatch strategy*: if the net demand is higher than L_d, the diesel generator is used. If it is lower, the batteries are used.
- *Load Following strategy*: the diesel generator never charges the batteries.

- *SOC_Setpoint strategy*: the diesel generator is on at full power, attempting to charge the batteries until the *SOC_Setpoint* is reached.
- Operation strategy of diesel at maximum power for a minimum time (charging the batteries).

Ashari and Nayar [43] propose an optimization method of the control strategies (based on [41]) of a PV–Diesel–Battery system with AC load, using *Setpoints* for the start-up and stop of the diesel generator and for the charging of batteries. The Diesel generator starts up when the voltage of the batteries is lower than a determined value or when the power of the inverter exceeds a determined percentage. The diesel generator stops when the power to be supplied is less than a certain percentage of its nominal power. The optimization of the control strategy variables is carried out by mathematically calculating the same in accordance with the parameters indicated in [41].

Muselli et al. [1,44] simulate a hybrid PV–Diesel–Battery system with only DC load in such a way that all the energy from the diesel generator goes through the batteries. The diesel generator works at nominal power, providing that the State of Charge (*SOC*) of the batteries is within determined limits (*SDM* and *SAR*, in % of the battery capacity). Simulations are carried out until the *SDM* and *SAR* values that allow determining the optimum system are obtained. The decrease in costs obtained with the hybrid system, when compared with the traditional photovoltaic system, is at least 20 or 30%. In addition, it has been concluded that the hybrid PV–Diesel–Battery system offers greater flexibility and efficiency than the PV–Battery system.

3. Design and control of stand-alone hybrid systems that include energy storage in hydrogen

The storage of energy in hydrogen is based on the conversion of DC electricity into hydrogen by means of an electrolyzer, storing the hydrogen generated and, whenever necessary, obtaining DC electricity from the hydrogen by means of fuel cells.

Over the past few years, there has been considerable progress in the development of hydrogen-related technologies, improving the efficiency of fuel cells and of the electrolyzers, and decreasing their costs. However, the current cost for this technology, as well as the low energy efficiency (about 25–35% of round trip efficiency [45] compared to about 80% for batteries), still make this storage system economically impractical [46].

Table 2 shows a summary of the most important papers on hybrid systems with hydrogen storage.

Lehman and Chamberlin [47] describe the operation of an autonomous PV–Hydrogen system with an alkaline fuel cell and an electrolyzer. Other authors [48–52] have carried out similar experiments, studying hybrid systems based on renewable sources with hydrogen storage.

Vosen and Keller [53] propose the economic optimization of photovoltaic systems with energy storage, using both batteries and hydrogen. Storage is compared using only batteries for storage, only using hydrogen, and with storage using both. The best economic results are obtained when using both storage systems. However, we should take into account the fact that the purchase costs of the fuel cell, electrolyzer, and hydrogen tank that are written about in this article are very low. This is the reason for the conclusion that hybrid storage is more economical than the battery-only storage; this conclusion is incorrect, as proven in [46]. In Vosen and Keller's paper, the control system determining how to store the excess energy (in the batteries or as hydrogen) and how to use the energy required to supply the demand is carried out in two ways: (1) by means of the *SOC* of the batteries and (2) by means of an adapted control based on neural networks. In both cases, the batteries have priority. The *SOC* method uses the batteries, provided the *SOC* is within certain limits. The second method also uses the *SOC* limits, but also uses a 24-hour predictive algorithm in order to, according to the authors, calculate the electrolyzer in a smaller size than in the first case, and, thus, obtain a more economical system, as the size of the electrolyzer depends on its input power, and, with the neural network method, power peaks from the photovoltaic generator can be avoided.

Kolhe et al. [54,55] analyze hybrid systems when hydrogen is used for energy storage in the long term, while batteries are used to store energy in the short term. The management of the energy stored is carried out by means of the *SOC* value of the batteries. The hourly simulation of the system is quite precise, but does not take into account costs.

Cotrell and Pratt [56] analyze systems involving PV generators, wind turbines, AC generators, electrolyzers, hydrogen tanks, fuel cells, and batteries; there are also some cases which utilized hydrogen internal combustion engines. The analysis is carried out using HOMER. In this paper, the authors carry out an exhaustive study of the purchase costs of the various components. Specifically, a system to supply a town in Alaska is considered, using the PV–Wind–Battery optimum design. The electricity supply to a telecommunications station is also optimized, obtaining the PV–Wind–Battery–Hydrogen optimum design (taking into account better cost, efficiency, and lifespan values of the electrolyzer and of the fuel cell than the current ones).

Agbossou et al. [57] studied a PV–Wind–Battery–Hydrogen system. The system was physically implemented and a series of DC electricity loads were programmed. The control was designed to maximize the energy flow from renewable sources to the loads and

Table 2
Publications on hybrid renewable—hydrogen.

	PV–Hydrogen	Wind–Hydrogen	PV–Wind–Hydrogen	PV–Hydrogen–Batteries	PV–Wind–Hydrogen–Batteries	Wind–Diesel–Hydrogen	Control strategy	Compare Hydrogen with Batteries	Compare Hydrogen with Diesel
Lehman and Chamberlin, 1991	×								
Vosen and Keller, 1999	×						×	×	
Kolhe et al., 2002, 2003				×	×		×	×	
Cotrell and Pratt, 2003					HOMER				
Agbossou et al., 2004					×			×	
Mills and Al-Hallaj, 2004					HYBRID2			×	×
Ulleberg, 2004				×			×		
Jossen et al., 2005				×	×			×	
Nelson et al., 2006			×					×	
García and Weisser, 2006						×	×		
Dufo-López et al., 2007				×	×	×	×		
Zoulias and Lymberopoulos, 2007	HOMER							×	×
Beccali et al., 2008	HOMER	HOMER							

to the electrolyzer, avoiding the use of batteries as an energy storage system as much as possible. Therefore, hydrogen is used as the main storage, while the batteries are used for auxiliary storage (to generate transitory current peaks and to absorb energy production peaks from renewable sources). The performance of the system was very satisfactory, indicating the benefits of the storage of energy in hydrogen instead of batteries in isolated systems. However, cost was not taken into account.

Mills and Al-Hallaj [58] carried out a simulation of a hybrid PV–Wind–Hydrogen system with a small battery. The simulation was conducted with the HYBRID2 program. The system performed well, although there was an over-dimensioning of the renewable sources (PV and wind), which generated more energy than that demanded by the load, given the low efficiency of the electricity–hydrogen–electricity energy conversion. It is also verified that with the current costs of these systems make them less than profitable when compared with the hybrid systems with renewable sources with batteries and diesel generators.

The optimization of the control strategies is a very important aspect of these systems. Ulleberg [59] shows the importance of the optimization of the control strategy of PV–Hydrogen–Battery systems, that of the performance of the system being very sensitive to relatively small changes in the control strategy. In this same paper, control strategies for PV–Hydrogen systems based on the performance of the electrolyzer and the fuel cell depending on the SOC value of the batteries are also included.

Jossen et al. [60] prove the technical advantages of the supply of energy by means of systems including both batteries and fuel cell (hydrogen storage) compared to those systems with only one of those components. In systems whose main storage resources are the batteries, when using fuel cell, the lifespan of the batteries is increased. On the other hand, in systems in which storage is in hydrogen, using auxiliary batteries for the power peaks, the necessary size of the fuel cell is reduced.

Nelson et al. [46] carried out an economic assessment of a hybrid PV–Wind–Hydrogen system, comparing it to a traditional hybrid PV–Wind–Battery system, concluding that, with current costs, the traditional system with battery storage is a great deal more economical than the hydrogen-storage system.

García and Weisser [61] present a method to optimize the design and control strategies of large power systems of the Wind–Diesel–Hydrogen type, studying an example to supply electricity to the Island of Granada. A diesel generator was designed to permanently work at a minimum of 30% of its capacity, while the power generated by the wind turbines was limited to a maximum penetration level of 30%. The system was studied at 1-hour intervals and the economic optimization of the component combination was carried out with lineal programming (minimizing the total cost of all the hours of the year). Two possible control strategies were used: supplying the demand not served by the wind turbines with priority over the diesel generators or with the fuel cells from the previously stored hydrogen.

Dufo-López et al. [62] present a novel strategy that can take into account up to 12 control variables, optimized by Genetic Algorithms, to control stand-alone hybrid renewable electrical systems. The optimized hybrid system can be composed of renewable sources (wind, PV and hydro), batteries, diesel generators, and hydrogen components.

Zoulias and Lymberopoulos [63] used HOMER for the study of the possible replacement of diesel generators and batteries with hydrogen energy storage in stand-alone power systems. Their conclusion is that this is technically viable, although, given the low energy efficiency of the electricity–hydrogen–electricity conversion, the renewable sources would be over dimensioned. Economically, a PV–Hydrogen system would be better when compared with a PV–Diesel system, as long as a 50% reduction in the cost of electrolyzers, and a 40% reduction in the cost of hydrogen tanks are made and the target of 300 €/kW for fuel cells in stationary applications is achieved.

Beccali et al. [64] used HOMER in order to compare the possible options for the supply of the electric and thermal loads of a small residential district in Palermo (Italy). The cost of energy (COE, the average cost per kWh of useful electricity) in the Wind–Hydrogen system is 4 times higher than in the use of grid electricity. In the case of the Wind–Hydrogen system, the COE is 9 times higher than in the use of grid electricity.

4. Multi-Objective design of stand-alone hybrid systems

When carrying out a design taking into account several objectives simultaneously, it is typical that some of them may be in conflict with some others [65]. Multi-Objective optimization attempts the simultaneous minimization of various objectives. There are some papers on Multi-Objective optimization of stand-alone hybrid systems. Those found after the review that were carried out to draft this paper are included below.

Pelet et al. [66] carried out an application of Multi-Objective Evolutionary Algorithms (MOEAs) [67] for the optimization of the cost and CO_2 emissions of an isolated system of a network in which three hotels and a town in the Tunisian Sahara were thermally and electrically supplied. The system consisted of photovoltaic panels, diesel generators, thermo-solar panels, a hot water accumulator, and cooling tower (Ranking cycle).

Bernal-Agustín et al. [68] present a Multi-Objective optimization (NPC versus CO_2 emissions) of hybrid PV–Wind–Diesel systems with battery storage. An MOEA was used, the hybrid system consisting of a photovoltaic generator, wind turbines, a diesel generator, and batteries.

Dufo-López and Bernal-Agustín [69] presented the triple Multi-Objective optimization (objectives to minimize: NPC, CO_2 emissions, and Unmet Load) of hybrid systems including hydrogen storage by means of MOEAs.

Bernal-Agustín and Dufo-López [70] presented a Multi-Objective design and control of hybrid systems minimizing NPC and Unmet Load.

5. Simulation and optimization software tools of hybrid systems

HOMER (Hybrid Optimization Model for Electric Renewables) [16], developed by NREL (National Renewable Energy Laboratory, USA), is the most-used optimization software for hybrid systems. It is able to optimize hybrid systems consisting of a photovoltaic generator, batteries, wind turbines, hydraulic turbines, AC generators, fuel cells, electrolyzers, hydrogen tanks, AC–DC bidirectional converters, and boilers. The loads can be AC, DC, and/or hydrogen loads, as well as thermal loads. The simulation is carried out using 1-hour intervals, during which all of the parameters (load, input and output power from the components, etc.) remain constant. The control strategies are based on [41]. It can be downloaded and used free of charge.

HYBRID2 [10,71] was developed by the Renewable Energy Research Laboratory (RERL) of the University of Massachusetts. It is a hybrid system simulation software. The hybrid systems may include three types of electrical loads, multiple wind turbines of different types, photovoltaic generators, multiple diesel generators, battery storage, and four types of power conversion devices. Other components, such as, for example, fuel cells or electrolyzers, can be modeled in the software. The simulation is very precise, as it can define time intervals from 10 min to 1 h. The possibilities with regard to control strategies are very high. NREL recommends optimizing the system with HOMER and then, once the optimum

Table 3
Hybrid simulation and/or optimization software tools.

	HOMER	HYBRID2	HOGA	HYDROGEMS + TRNSYS	HYBRIDS	INSEL	HYBRIDS	ARES	RAPSIM	SOMES	SOLSIM
Free download and use	×	×	×								
PV, Diesel, Batteries	×	×	×	×	×	×	×	×	×	×	×
Wind	×	×	×	×	×	×	×		×	×	×
Mini-Hydro	×	×	×	×							
Fuel cell; electrolyzer and hydrogen tank	×	×	×	×							
Hydrogen load	×	×	×	×							
Thermal load	×			×							
Control strategies	×	×	×								
Simulation	×	×	×	×	×	×	×	×	×	×	×
Economical Optimization	×		×	×							
Multi-Objective optimization, Genetic Algorithms			×								

system is obtained, improving the design using HYBRID2. It can be downloaded and used free of charge.

HOGA [42] is a hybrid system optimization program developed by the Electric Engineering Department of the University of Zaragoza (Spain). The optimization is carried out by means of Genetic Algorithms, and can be Mono-Objective or Multi-Objective. It allows optimizing of hybrid systems consisting of a photovoltaic generator, batteries, wind turbines, hydraulic turbine, AC generator, fuel cells, electrolyzer, hydrogen tank, rectifier, and inverter. The loads can be AC, DC, and/or hydrogen loads. The simulation is carried out using 1-hour intervals, during which all of the parameters remained constant. The control strategies are optimized using Genetic Algorithms. It can be downloaded and used free of charge.

TRNSYS (Transient Energy System Simulation Program) [72] is an energy system simulation software, developed in Fortran in 1975 by the University of Wisconsin and the University of Colorado (USA). It was initially developed to simulate thermal systems, but, over the years, it has also become a hybrid system simulator, including photovoltaic, thermal solar, and other systems. The standard TRNSYS library includes many of the components commonly found in thermal and electrical renewable energy systems. The simulation is carried out with great precision, allowing the viewing of graphics with great detail and precision. However, it does not allow the carrying out of optimizations. It is not free of charge.

HYDROGEMS [73,74] is not a program, but a series of libraries developed at the Institute for Energy Technology (IFE, Norway). The libraries are used by TRNSYS and by Engineering Equation Solver (EES) software. The libraries developed by HYDROGEMS model the following components: photovoltaic generators, wind turbines, diesel generators, polymeric and alkaline fuel cells, electrolyzers, hydrogen tanks, lead-acid batteries, and DC/AC converters. It is possible to carry out economic optimization, if it is used with the GenOpt [75] software, using the lineal simplex optimization method. These libraries are free for TRNSYS users.

HYBRIDS [36] is a simulation and economic evaluation program for PV–Wind–Diesel–Battery systems. It used 1-hour intervals in the simulation and it calculated the NPC. This software is not available.

INSEL [76] was developed at the University of Oldenburg and allows the simulation of renewable energy systems. The user selects blocks from its library and connects them in order to define the structure of the system. The system operation analysis can be carried out with a time frame specified by the user. The flexibility to create the system models and configurations is a very interesting feature. It is a simulation, but not an optimization program. It is not free of charge.

ARES is a program developed at the University of Cardiff [21] which very precisely simulates PV–Wind–Battery systems. This software is not available.

RAPSIM (Remote Area Power Supply Simulator) [77] was created at the University of Murdoch in Perth, Australia. This software is used to select hybrid PV–Wind–Diesel–Battery systems. The total costs throughout the lifespan are calculated. The user can modify the components in order to see the effect on the total cost. It is basically a simulation software (although the cost of the system throughout its lifespan is obtained). It is not free of charge.

SOMES [78] has been developed at Utrecht University (The Netherlands). This software can simulate the performance of renewable energy systems. The energy system can be composed of renewable energy sources (PV arrays and wind turbines), a motor generator, a grid, battery storage, and several types of converters. It is not free of charge.

SOLSIM [79] was developed in Fachhochschule Konstanz (Germany). It has models for photovoltaic panels, wind turbines, diesel generators, and batteries. There is the possibility of including biogas and biomass generators to generate electricity and heat. It simulates the operation of the system and carries out an economic analysis. The control options are very limited, optimizing only the panel inclination angles. This software is not available.

Table 3 summarizes the characteristics of the simulation and/or optimization software tools.

6. Conclusions

Stand-alone electric generation hybrid systems are generally more suitable than systems that only have one energy source for the supply of electricity to off-grid applications, especially in remote areas with difficult access. However, the design, control, and optimization of the hybrid systems are usually very complex tasks.

This paper has included the most relevant papers on the design, simulation, control, and optimization of the hybrid systems. As a result of this review, we determined that the most frequent systems are those consisting of a PV Generator and/or Wind Turbines and/or Diesel Generator, with energy storage in lead-acid batteries. Energy storage in hydrogen, although technically viable, has a drawback in terms of its low efficiency in the electricity–hydrogen–electricity conversion process, besides the fact that, economically, it cannot compete with battery storage at the present time.

An aspect that became clear, after the review had been carried out, is the paucity of researchers writing papers about multi-objective optimum designs in hybrid systems. However, the importance of considering other objectives besides the cost is evident, such as, for example, contaminating emissions or reliability.

Finally, the design and simulation tools that have been developed over the past few years have been briefly described,

highlighting the fact that some of them can be downloaded and used free of cost.

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